GAMMA RAYS

Exponential Absorption

The attenuation of gamma radiation (photons) by an absorber is qualitatively different from that of either alpha or beta radiation. Whereas both these corpuscular radiations have definite ranges in matter and therefore can be completely stopped ,gamma radiation can only be reduced in intensity by increasingly thicker absorbers; it cannot be completely absorbed.

If γ attenuation measurements are made under conditions of good geometry, that is, with a well collimated, narrow beam of radiation, as shown in Fig 3-1, and if the data are plotted on semilog paper, a straight line results, as shown in Fig.3-2, if the γ rays are monoenergetic.

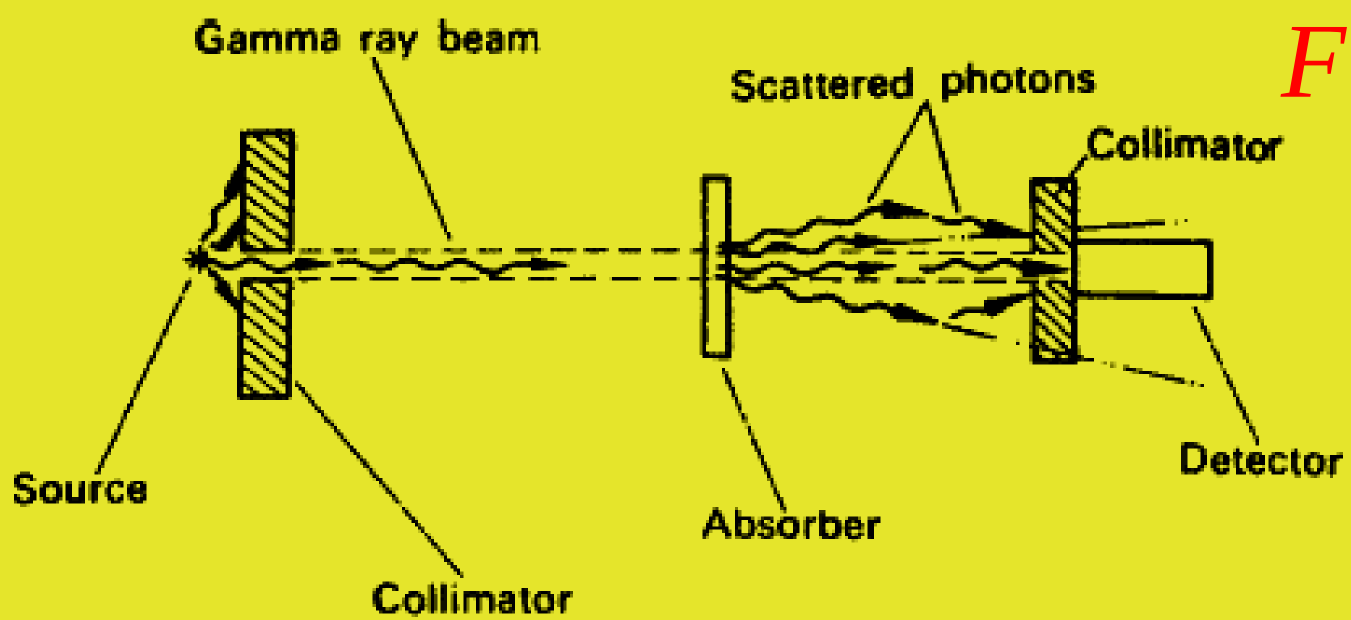


Fig 3-1

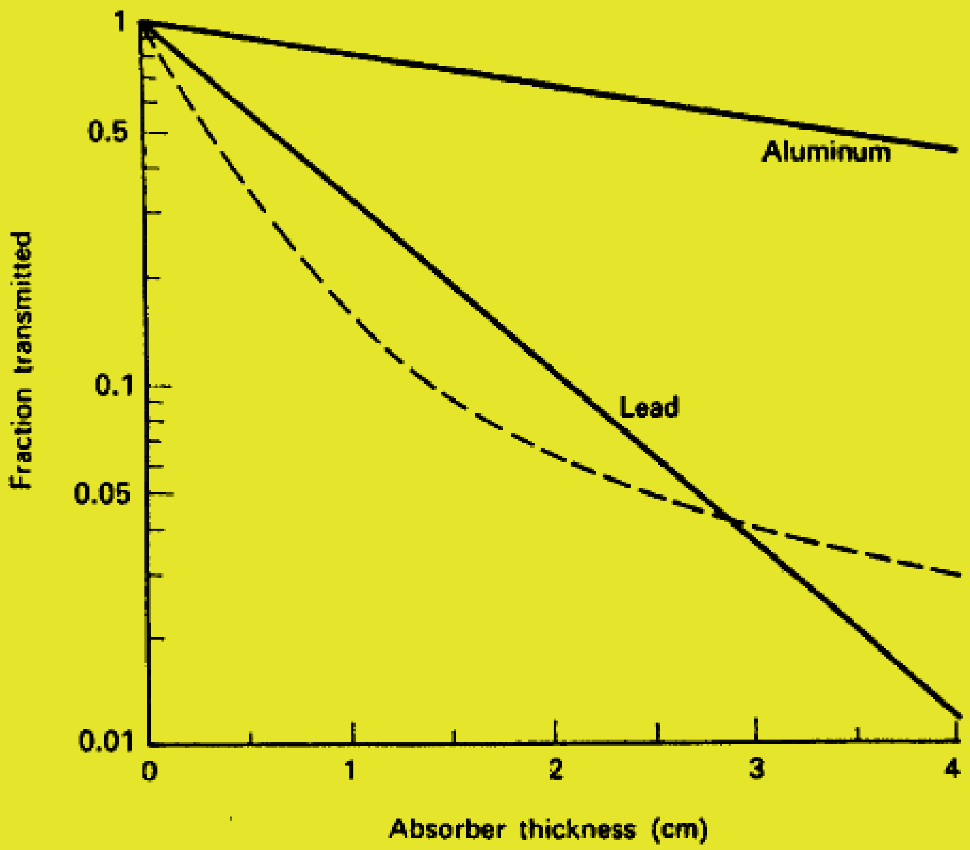


Figure 3-2. Attenuation of γ rays under conditions of good geometry. The solid lines are the attenuation curves for 0.662-MeVmonoenergetic γ rays. The dotted line is the attenuation curve for a heterochromatic beam.

The equation of the straight line in Fig 3-2 is;

$$\ln I = -\mu t + \ln I_0$$

Or

$$\ln \frac{I}{I_0} = -\mu t.$$

$$\frac{I}{I_0} = e^{-\mu t}, \qquad (3\text{-}1)$$

where

I_0 = gamma-ray intensity at zero absorber thickness,
t = absorber thickness,
I = gamma-ray intensity transmitted through an absorber of thickness t,
e = base of the natural logarithm system, and
μ = slope of the absorption curve = the attenuation coefficient.

Since the exponent in an exponential equation must be dimensionless, μ and t must be in reciprocal dimensions, that is, if the absorber thickness is measured in cm, then the attenuation coeff. is called the linear attenuation coeff.,μ_l, its unit cm^{-1}. If t is in g/cm^2 , then the absorption coeff.is called the mass attenuation coeff., μ_m, its unit cm^2/g. The numerical relationship between μ_l and μ_m, for a material whose density is ρ g/cm3, is given by the equation:

$$\mu_l \, \mathrm{cm}^{-1} = \mu_m \frac{\mathrm{cm}^2}{\mathrm{g}} \times \rho \frac{\mathrm{g}}{\mathrm{cm}^3}. \quad (3\text{-}2)$$

For some purposes, it is useful to use the atomic attenuation coeff., μ_a. The atomic attenuation coeff. is the fraction of an incident gamma-ray beam that is attenuated by a single atom. Another way of saying the same thing is that the atomic attenuation coeff. is the probability that an absorber atom will interact with one of the photons in the beam. The atomic attenuation coeff. may be defined by the equation

$$\mu_a \ \mathrm{cm}^2 = \frac{\mu_1 \dfrac{1}{\mathrm{cm}}}{N \dfrac{\mathrm{atoms}}{\mathrm{cm}^3}}, \qquad (3\text{-}3)$$

where N is the number of absorber atoms per cm^3. Note that the dimensions of μ_a are cm^2, the units of area. For this reason, the atomic attenuation coeff. Is almost always referred to as the cross section of the absorber. The unit in which the cross section is specified is the barn ,b ($1b = 10^{-24}\ cm^2$).

Linear absorption ceff. of some materials

	ρ, (g/cm^3)	QUANTUM ENERGY (MeV)												
		0.1	0.15	0.2	0.3	0.5	0.8	1.0	1.5	2	3	5	8	10
C	2.25	0.335	0.301	0.274	0.238	0.196	0.159	0.143	0.117	0.100	0.080	0.061	0.048	0.044
Al	2.7	0.435	0.362	0.324	0.278	0.227	0.185	0.166	0.135	0.117	0.096	0.076	0.065	0.062
Fe	7.9	2.72	1.445	1.090	0.838	0.655	0.525	0.470	0.383	0.335	0.285	0.247	0.233	0.232
Cu	8.9	3.80	1.830	1.309	0.960	0.730	0.581	0.520	0.424	0.372	0.318	0.281	0.270	0.271
Pb	11.3	59.7	20.8	10.15	4.02	1.64	0.945	0.771	0.579	0.516	0.476	0.482	0.518	0.552
Air	1.29×10^{-3}	1.95×10^{-4}	1.73×10^{-4}	1.59×10^{-4}	1.37×10^{-4}	1.12×10^{-4}	9.12×10^{-5}	8.45×10^{-5}	6.67×10^{-5}	5.75×10^{-5}	4.6×10^{-5}	3.54×10^{-5}	2.84×10^{-5}	2.61×10^{-5}
H_2O	1	0.167	0.149	0.136	0.118	0.097	0.079	0.071	0.056	0.049	0.040	0.030	0.024	0.022
Concrete[a]	2.35	0.397	0.326	0.291	0.251	0.204	0.166	0.149	0.122	0.105	0.085	0.067	0.057	0.054

The atomic attenuation coeff. is also called the microscopic cross section and is symbolized by σ, while the linear attenuation coeff. is often called the macroscopic cross section and is given by the symbol Σ. This nomenclature is almost always used in dealing with neutrons. Equation (3-3) can thus be written as

$$\sum \text{cm}^{-1} = \sigma \frac{\text{cm}^2}{\text{atom}} \times N \frac{\text{atoms}}{\text{cm}^3}. \qquad (3\text{-}4)$$

Using equations (3-1and 4),one can get

$$\frac{I}{I_0} = e^{-\mu_a t} = e^{-\sigma N t}. \qquad (3\text{-}5)$$

The linear attenuation coefficient for a mixture of materials or an alloy is given by

$$\mu_1 = \mu_{a1} \times N_1 + \mu_{a2} \times N_2 + \cdots = \sum_{n=1}^{n} \mu_{an} \times N_n, \qquad (3\text{-}6)$$

where

μ_n = atomic coefficient of the nth element and
N_n = number of atoms per cm^3 of the nth element.

EXAMPLE (3-1)

Aluminum bronze, an alloy containing 90% Cu (atomic weight = 63.57) and 10% Al (A= 26.98) by weight, has a density of 7.6 g/cm^3. What are the μ_l and μ_m for 0.4-MeV γ rays if the cross sections for Cu @ Al for this quantum energy are 9.91 and 4.45 b

Solution

From Eq. (3-6), the linear attenuation coeff. of ***aluminum bronze is***

$$\mu_l = (\mu_a)_{Cu} \times N_{Cu} + (\mu_a)_{Al} \times N_{Al}.$$

The number of Cu atoms per cm^3 in the alloy is

$$N_{Cu} = \frac{6.02 \times 10^{23} \text{ atoms/mol}}{63.57 \text{ g/mol}} \times (7.6 \times 0.9) \ \frac{\text{g}}{\text{cm}^3} = 6.5 \times 10^{22} \ \frac{\text{atoms}}{\text{cm}^3}$$

and for Al, it is given by

$$N_{Al} = \frac{6.02 \times 10^{23} \text{ atoms/mol}}{27 \ \frac{\text{g}}{\text{mol}}} \times (7.6 \times 0.1) \ \frac{\text{g}}{\text{cm}^3} = 1.7 \times 10^{22} \ \frac{\text{atoms}}{\text{cm}^3}.$$

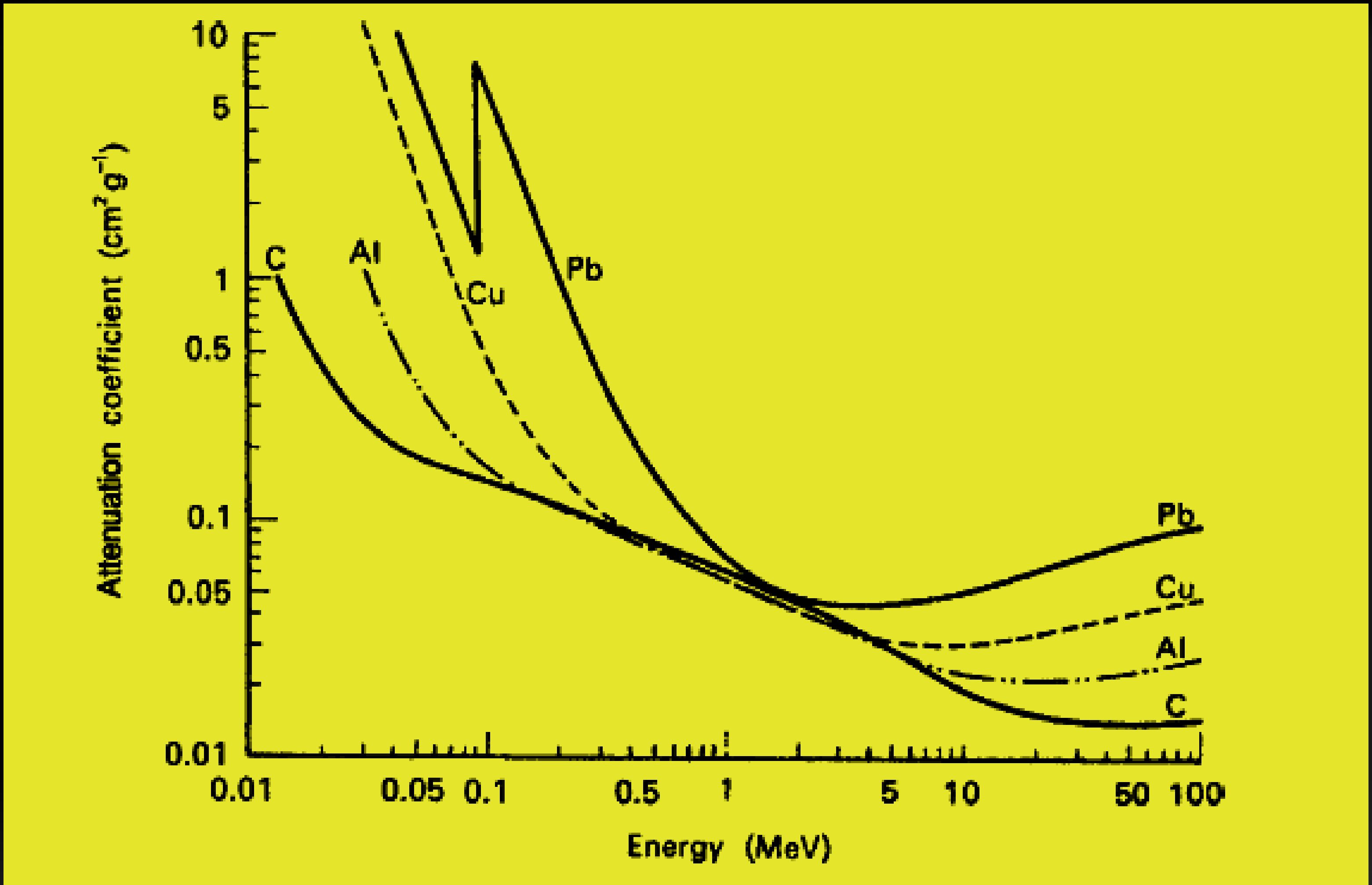
The linear attenuation coefficient therefore is

$$\mu_l = 9.91 \times 10^{-24} \ \frac{\text{cm}^2}{\text{atom}} \times 6.5 \times 10^{22} \ \frac{\text{atoms}}{\text{cm}^3} + 4.45 \times 10^{-24} \ \frac{\text{cm}^2}{\text{atom}} \times 1.7 \times 10^{22} \ \frac{\text{atoms}}{\text{cm}^3} = 0.72 \text{ cm}^{-1}.$$

Using eq.(3-2) to find μ_m

$$\mu_m = \frac{\mu_l}{\rho} = \frac{0.72 \text{ cm}^{-1}}{7.6 \text{ g/cm}^3} = 0.095 \ \frac{\text{cm}^2}{\text{g}}.$$

The attenuating properties of matter vary systematically with the atomic number of the absorber and with the energy of the gamma radiation, as shown in Fig.3-2. It should be noted, however, that in the region where the Compton effect (this effect is more fully discussed below) predominates, the mass attenuation coeff. is almost independent of the atomic number of the absorber (Fig.3-3)



Attenuation coefficient (cm² g⁻¹)
10
5
1
0.5
0.1
0.05
0.01
C
Al
Cu
Pb
Pb
Cu
Al
C
0.01
0.05
0.1
0.5
1
5
10
50
100
Energy (MeV)

(Fig.3-3)

EXAMPLE (3-2)

(a) Compute the thickness of Al and Pb to transmit 10% of a narrow beam of 0.1-MeV gamma radiation.

μ_l for Al is 0.435 cm^{-1}, and for Pb it is 59.7 cm^{-1}

$$\frac{I}{I_0} = e^{-\mu t} = \frac{1}{10} = e^{-(0.435\,\mathrm{cm}^{-1})(t\,\mathrm{cm})}$$

$$\ln 10 = 0.435\, t$$

$$t = \frac{\ln 10}{0.435} = \frac{2.3}{0.435} = 5.3\,\mathrm{cm\ Al.}$$

In a similar manner, we have for Pb:

$$\frac{1}{10} = e^{-(59.7\,\mathrm{cm}^{-1})(t\,\mathrm{cm})}$$

$$t = \frac{2.3}{59.7\,\mathrm{cm}^{-1}} = 0.04\,\mathrm{cm\ Pb.}$$

(b) Repeat part (a) for a 1.0-MeV gamma ray; given μ_l for Al = 0.166 cm^{-1} and μ_l for Pb = 0.771 cm^{-1}.

(c) Compare the density thickness of the Al and Pb in each part of the illustrative example above.

For Al, we have

$$\frac{1}{10} = e^{-(0.166\,\mathrm{cm}^{-1})(t\,\mathrm{cm})}$$
$$t = 13.9\ \mathrm{cm\ Al}$$

and for Pb,

$$\frac{1}{10} = e^{-(0.771\,\mathrm{cm}^{-1})(t\,\mathrm{cm})}$$
$$t = 3\ \mathrm{cm\ Pb.}$$

$t_d\,(\mathrm{Al}) = 2.7\,\mathrm{g/cm^3} \times 5.3\,\mathrm{cm} = 14.3\,\mathrm{g/cm^2}$ and
$t_d\,(\mathrm{Pb}) = 11.34\,\mathrm{g/cm^3} \times 0.04\,\mathrm{cm} = 0.45\,\mathrm{g/cm^2}$.

For the 1.0-MeV photons, the density thicknesses for the Al and Pb are given as follows:

$t_d\,(\mathrm{Al}) = 2.7\,\mathrm{g/cm^3} \times 13.9\,\mathrm{cm} = 37.5\,\mathrm{g/cm^2}$ and
$t_d\,(\mathrm{Pb}) = 11.34\,\mathrm{g/cm^3} \times 3\,\mathrm{cm} = 34\,\mathrm{g/cm^2}$.

Example 3-2 shows that for high-energy γ rays, Pb is only a slightly better absorber, on a mass basis, than Al. For low-energy photons, on the other hand, Pb is a very much better absorber than Al. Generally, for energies between about 0.75 and 5 MeV, almost all materials have, on a mass basis, about the same γ-ray attenuating properties. To a first approximation in this energy range, therefore, shielding properties are approximately proportional to the density of the shielding material.

For lower and higher quantum energies, absorbers of high (Z) are more effective than those of low (Z). To understand this behavior, one must examine the microscopic mechanisms of the interaction between γ rays and matter.

Half Value Layer and Tenth Value Layer

The half value layer (HVL) is defined as the thickness of a shield or an absorber that reduces the radiation level by a factor of 2, that is to half the initial level. (The HVL is also called a half value thickness.)

The shield thickness necessary to reduce the intensity of a beam, under conditions of good geometry, to 1/2 is calculated from Eq. (3-7) in the following manner:

$$\frac{I}{I_0} = \frac{1}{2} = e^{-\mu t}$$

$$\ln\frac{1}{2} = -0.693 = -\mu t_{1/2}$$

$$t_{1/2} = \frac{0.693}{\mu} = \text{HVL}. \qquad (3\text{-}7)$$

When calculating shielding thickness, it may be convenient to determine the number of HVLs required to reduce the radiation to the desired level. For example, to reduce the radiation level to 1/10 its original level would require between 3 HVLs (which would reduce the level to $1/2^3 = 1/8$) and 4 HVLs (which would reduce the beam to $1/2^4 = 1/16$). Generally, the number of HVLs (n) required to reduce the beam level from I_0 to I is given by

$$\frac{I}{I_0} = \frac{1}{2^n}. \qquad (3\text{-}8)$$

To calculate the NO of HVLs to reduce the γ ray beam level to 10%, as in Ex 3-2 using Eq. (3-8):

$$\frac{I}{I_0} = \frac{1}{10} = \frac{1}{2^n}$$

$$n = 3.3\ \text{HVLs}.$$

For the case of 1-MeV gammas, whose $\mu_1 = 0.166\ \text{cm}^{-1}$,

$$HVL = \frac{0.693}{\mu_1} = \frac{0.693}{0.166\ \text{cm}^{-1}} = 4.17\ \text{cm Al}.$$

Therefore,

$$\text{Shield thickness} = 3.3\ \text{HVL} \times 4.17 \frac{\text{cm Al}}{\text{HVL}} = 13.8\ \text{cm Al}.$$

A shield that will attenuate a γ beam to 10% of its radiation level, this shield thickness, is called a tenth value layer, which is symbolized by TVL. The concepts of HVLs and TVLs are widely used in shielding design.

Interaction Mechanisms

For radiation protection purposes, four major mechanisms for the interaction of γ-ray energy are considered significant. Two of these mechanisms, photoelectric absorption and Compton scattering, which involve interactions only with the orbital electrons of the absorber, predominate in the case where the quantum energy of the photons does not greatly exceed 1.02 MeV, the energy equivalent of the rest mass of two electrons.

In the case of higher-energy photons, pair production, which is a direct conversion of electromagnetic energy into mass, occurs. These three gamma-ray interaction mechanisms result in the emission of electrons from the absorber. Very high-energy photons, $E > 2m_0c^2$, may also be absorbed into the nuclei of the absorber atoms; they then initiate photonuclear reactions that result in the emission of other radiations from the excited nuclei.

Pair Production

A photon whose energy exceeds 1.02 MeV may, as it passes near a nucleus, spontaneously disappear, and its energy reappears as a e^+ and an e^- as pictured in Fig 3-4. Each of these two particles has a mass of m_0c^2, or 0.51 MeV, and the total kinetic energy of the two particles is very nearly equal to E (gamma) – $2m_0c^2$.

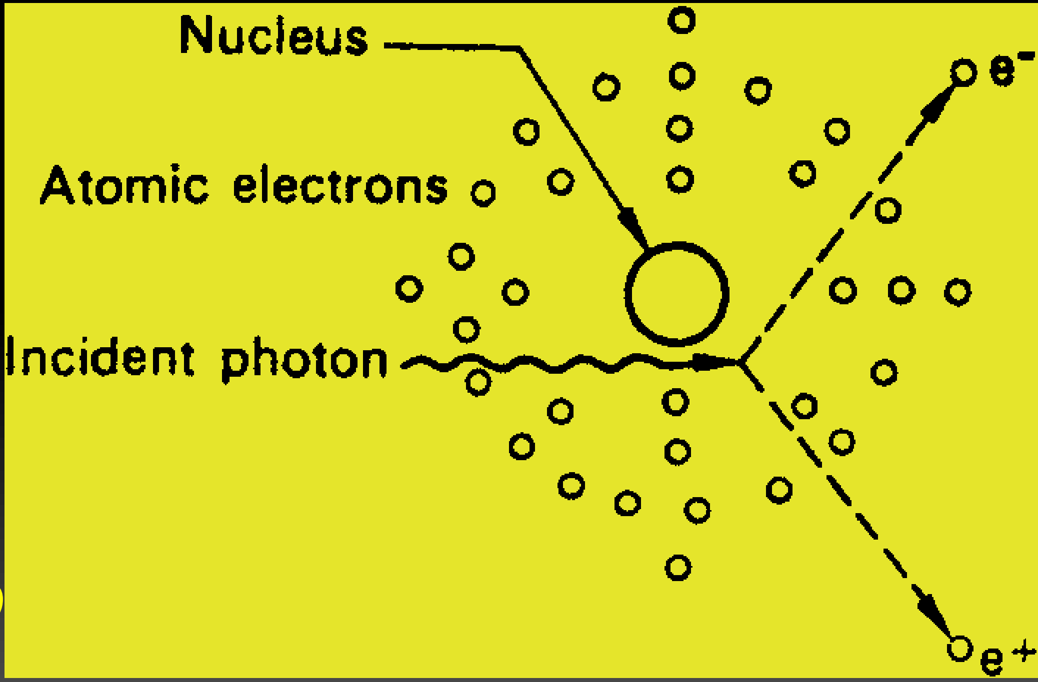


Fig 3-4

This transformation of energy into mass must take place near a particle, such as a nucleus, for the momentum to be conserved. The kinetic energy of the recoiling nucleus is very small. For practical purposes, therefore, all the photon energy in excess of that needed to supply the mass of the pair appears as K.E. of the pair. This same phenomenon may also occur in the vicinity of an e, but the probability of occurrence near a nucleus is very much greater. Furthermore, the threshold energy for pair production near an electron is $4m_0c^2$.

The cross section, or the probability of the production of a positron–electron pair, is approximately proportional to $Z^2 + Z$ and is therefore increasingly important as the Z of the absorber increases. The cross section increases slowly with increasing energy between the threshold of 1.02 MeV and about 5 MeV. For higher energies, the cross section is proportional to the logarithm of the quantum energy.

This increasing cross section with increasing quantum energy above the 1.02-MeV threshold accounts for the increasing attenuation coefficient, shown in Fig 3-4, for high-energy photons. Note that the curves for each of the coefficients have a minimum value; for lead, the minimum attenuation is for 3-MeV (γ rays).

After production of a pair, the e^+ and e^- are projected in a forward direction (relative to the direction of the photon) and each loses its K.E by excitation, ionization, and bremsstrahlung, as with any other high-energy electron.

When the positron has expended all of its kinetic energy, it combines with an e^- and the masses of the two particles are converted to energy in the form of two quanta of 0.51 MeV each of annihilation radiation. Thus, a 10-MeV photon may, in passing through a lead absorber, be converted into a positron–electron pair in which each particle has about 4 MeV of kinetic energy.

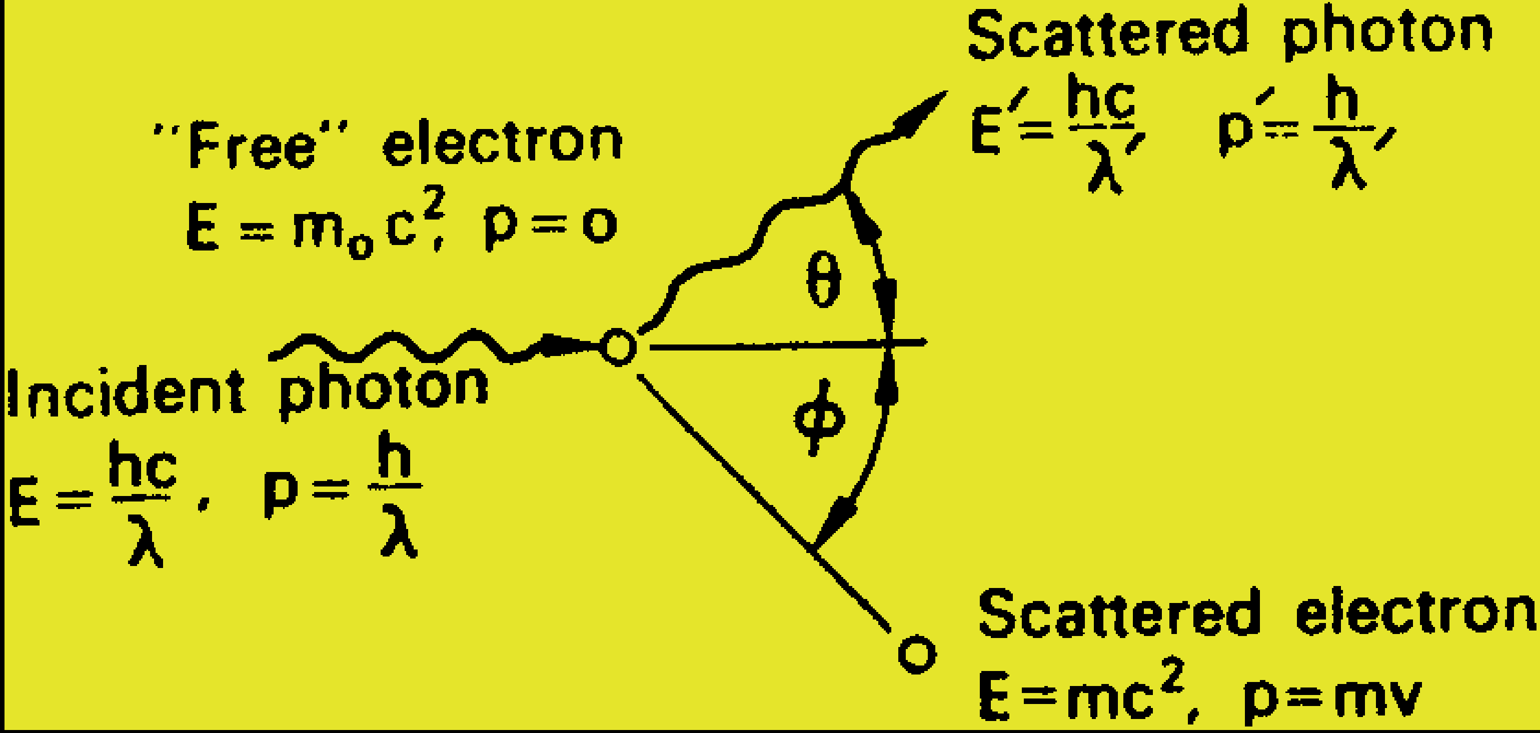
This K.E is then dissipated in the same manner as beta particles. The positron is then annihilated by combining with an electron in the absorber, and two photons of 0.51 MeV each may emerge from the absorber (or they may undergo Compton scattering or photoelectric absorption). The net result of the pair production interaction in this case was the conversion of a single 10-MeV photon into two photons of 0.51 MeV each and the dissipation of 8.98 MeV of energy.

Compton Scattering

Compton scattering is an elastic collision between a photon and a "free" electron (an e^- whose binding energy to an atom is very much less than the energy of the photon), as shown diagrammatically in Figure 3-5.

In a collision between a photon and a free e^-, it is impossible for all the photon's energy to be transferred to the electron if momentum and energy are to be conserved.

Fig 3-5



This can be shown by assuming that such a reaction is possible. If this were true, then, according to the conservation of energy, all the energy of the photon is imparted to the electron, and we have, from Eq.

$$E = mc^2.$$

According to the law of conservation of momentum, all the momentum p of the photon must be transferred to the electron if the photon is to disappear:

$$p = \frac{E}{c} = mv. \quad (3\text{-}9)$$

Eliminating m from these two equations and solving for v, we find v =c , an impossible condition. The original assumption, that the photon transferred all of its energy to the electron, must therefore be false.

Since all the photon's energy cannot be transferred, the photon must be scattered,and the scattered photon must have lesser energy or a longer wavelength than the incident photon. Only the energy difference between the incident and scattered photon is transferred to the free electron. The amount of energy transferred in any collision can be calculated by applying the laws of conservation of energy and momentum to the situation pictured in Figure 3-5. To conserve energy, one will get ;

$$\frac{hc}{\lambda} + m_0 c^2 = \frac{hc}{\lambda'} + mc^2 \qquad (3\text{-}10)$$

$$\frac{h}{\lambda} = \frac{h}{\lambda'} \cos\theta + mv\cos\phi \qquad (3\text{-}11)$$

$$0 = \frac{h}{\lambda'} \sin\theta - mv\sin\phi. \qquad (3\text{-}12)$$

The solution of these equations shows the change in wavelength of the photon to be

$$\Delta\lambda = \lambda' - \lambda = \frac{h}{m_0 c}(1 - \cos\theta) \text{ cm} \qquad (3\text{-}13)$$

$$\Delta\lambda = 0.0242(1 - \cos\theta) \text{ Å}. \qquad (3\text{-}14)$$

Equation (3.14) shows that the change in λ following a scattering event depends only on the scattering angle; it neither depends on the energy of the incident photon nor on the nature of the scatterer. As a consequence, a low-energy, long λ photon will lose a smaller percentage of its energy than a high-energy, short- λ photon for the same scattering angle. The relation between the scattering angles of the photon and the electron is:

$$\cot\frac{\theta}{2} = \left\{1 + \frac{h}{\lambda m_0 c}\right\} \tan\phi. \tag{3-15}$$

Eq. (3-15) shows that the e^- cannot be scattered through an angle greater than 90◦. This scattered e^- is of great importance in radiation dosimetry because it is the vehicle by means of which energy from the incident photon is transferred to an absorbing medium. The Compton e dissipates its K.E in the same manner as a beta particle and is one of the primary ionizing particles produced by gamma radiation (photons).

Compton scattering is also important in health physics engineering because energetic γ loses a greater fraction of its energy when it is scattered than a low-energy γ does. By taking advantage of this fact, the required shielding thickness can be reduced.

EXAMPLE 3-3

What percentage of their energies do 1-MeV and 0.1-MeV photons lose if they are scattered through an angle of 90°?

Solution

(1) calculating the wavelength of the photons before and after the scattering event.
(2) Converting the scattered λs into the corresponding energies.
(3) Calculating the percent energy loss of each photon.

Using Eq. (1-15)

$$\lambda(0.1\,\text{MeV}) = \frac{12,400}{\text{eV}} = \frac{1.24\times10^4}{1\times10^5} = 0.124\,\text{Å}$$

$$\lambda(1.0\,\text{MeV}) = \frac{12,400}{\text{eV}} = \frac{1.24\times10^4}{1\times10^6} = 0.0124\,\text{Å}$$

The wavelength change due to the scatter depends only on the scattering angle, as given by Eq. (3-14). λ is therefore the same for both photons.

$$\Delta\lambda = 0.0242(1-\cos\theta) = 0.0242\,(1-\cos 90^\circ) = 0.0242\,\text{Å}.$$

- The wavelength of each photon after scattering is

$$\lambda'(0.1\ \text{MeV}) = \lambda + \Delta\lambda = 0.124 + 0.0242 = 0.1482\,\text{Å}$$

$$\lambda'(1.0\,\text{MeV}) = \lambda + \Delta\lambda = 0.0124 + 0.0242 = 0.0366\,\text{Å}.$$

- The energy of each scattered photon, E' is

$$E'(0.1482\,\text{Å}) = \frac{12,400}{0.1482\ \text{Å}} = 83,670\,\text{eV} = 0.08367\ \text{MeV}$$

$$E'(0.0366\,\text{Å}) = \frac{12,400}{0.0366\ \ \text{Å}} = 338,500\,\text{eV} = 0.3385\ \text{MeV}.$$

- The percentage decrease in the energy each of the photons is

$$\Delta E(1.0\,\text{MeV}) = E - E' = \frac{1.0000\ \text{MeV} - 0.3385\ \text{MeV}}{1.0000\,\text{MeV}} \times 100 = 66.2\%$$

$$\Delta \text{E}\ (0.1\ \text{MeV}) = E - E' = \frac{0.10000\ \text{MeV} - 0.08367\ \text{MeV}}{0.10000\,\text{MeV}} \times 100 = 16.3\%.$$

The probability of a Compton interaction with an e^- decreases with increasing quantum energy and is independent of the Z of the interacting material. In C.S, every e^- acts as a scattering center and the bulk scattering properties of matter depends mainly on the e^- density per unit mass. Probabilities for C.S are therefore given on a per-electron basis. The theoretical cross sections for Compton scattering were derived by Klein and Nishina.

For scattering into a differential solid angle dΩ at an angle θ to the direction of the incident photon (Fig.3-6) they give the differential total scattering coefficient as

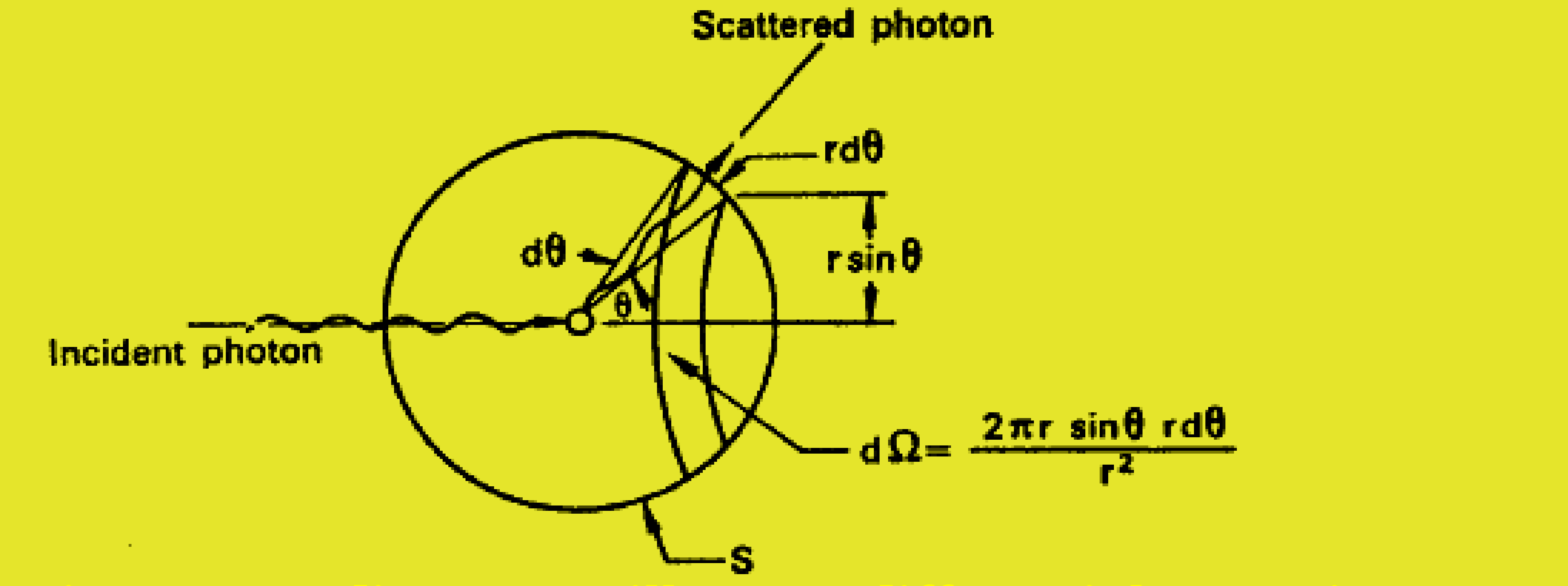
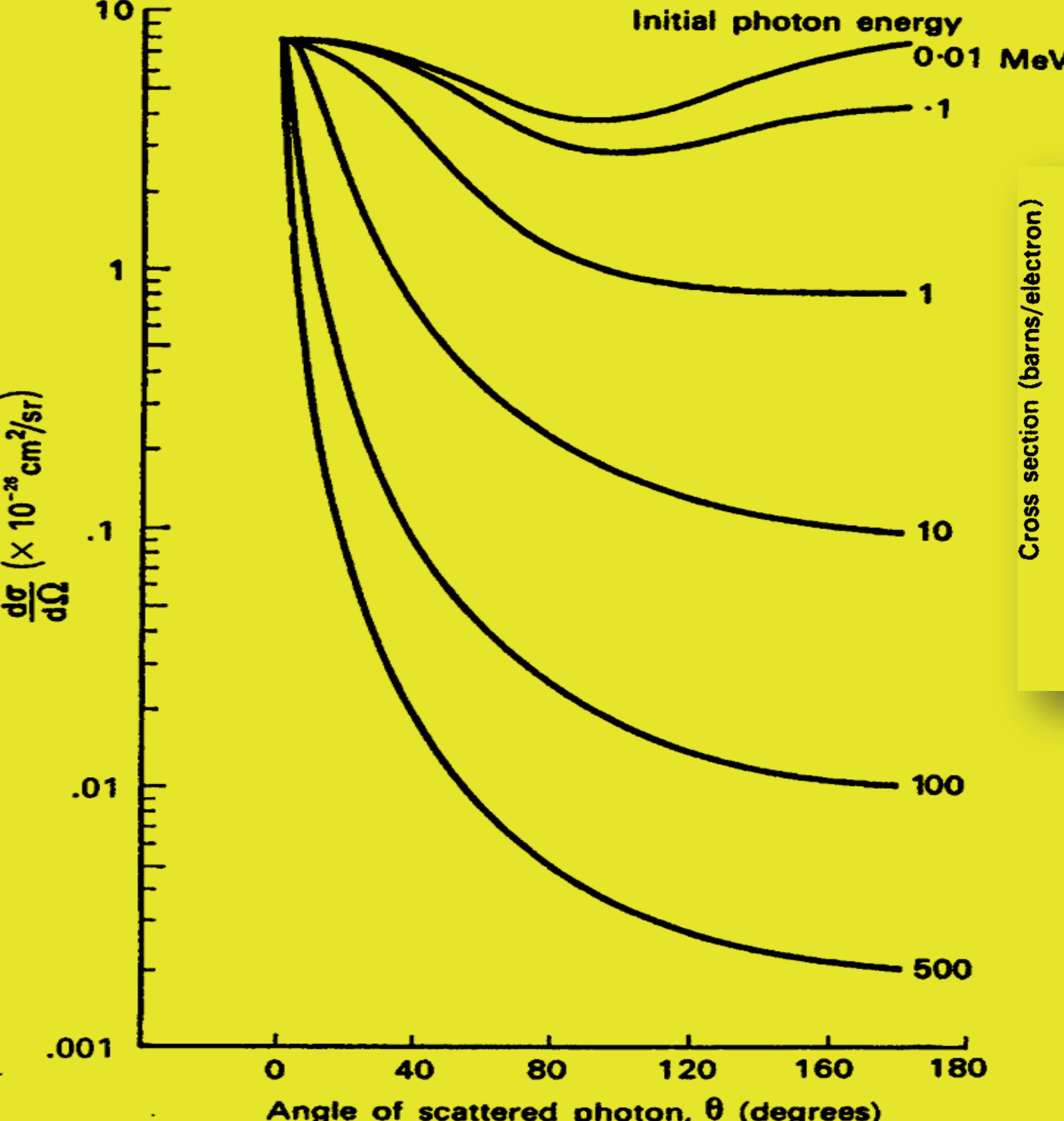


Fig 3-6. C S diagram to illustrate differential scattering cross section. S is a sphere of unit radius whose center is the scattering e

$$\frac{d\sigma_t}{d\Omega}=\frac{e^4}{2m_0^2c^4}\left[\frac{1}{1+a(1-\cos\theta)}\right]^2\left[\frac{1+\cos^2\theta+a^2(1-\cos\theta)^2}{1+a(1-\cos\theta)}\right], \quad (3\text{-}16)$$

where e , m_0, and c have the usual meaning and a = hf/m_0c^2. Eq. (3.16) and Fig.3-7 gives the probability of scattering a photon into a solid angle dΩ through an angle θ. The total probability of scattering, , can be obtained by substituting d = 2π sin θ dθ and integrating the differential scattering coeff. over the entire sphere. The result of this calculation, for γ photon up to 10 MeV, is presented graphically in Fig3-8



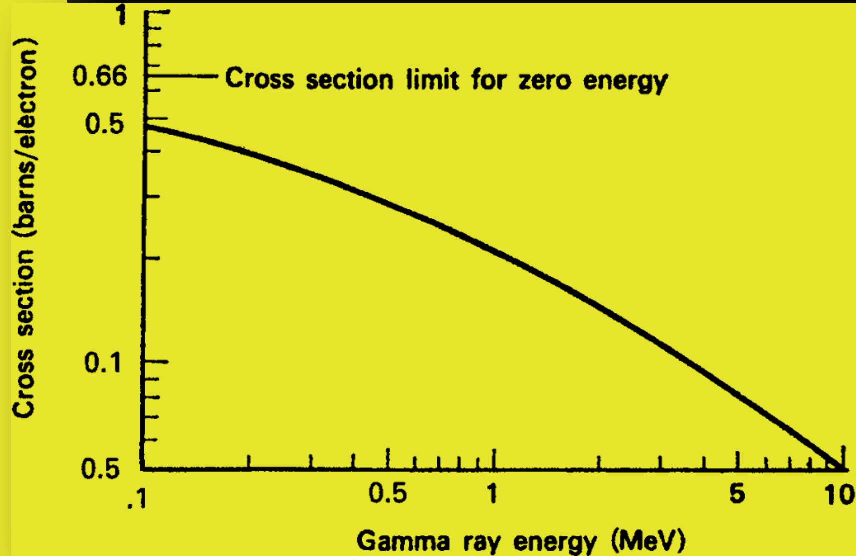


Figure 3-8. Total Compton cross section for a free electron.

Fig 3-7. Differential scattering coeff.showing the probable angular distribution of Compton-scattered

Photonuclear Reactions (Photodisintegration)

The photoelectric effect, in which the photon disappears, is an interaction between a photon and a tightly bound electron whose binding energy is equal to or less than the energy of the photon. The primary ionizing particle resulting from this interaction is the photoelectron, whose energy is given by

$$E_{\mathrm{pe}} = hf - \phi.$$

The photoelectron dissipates its energy in the absorbing medium mainly by excitation and ionization. The binding energy φ is transferred to the absorber by means of the fluorescent radiation that follows the initial interaction. These low-energy photons are absorbed by outer es or in other photoelectric interactions not far from their points of origin. The photoelectric effect is favored by low-energy photons and high-atomic-numbered absorbers.

The cross section for this reaction varies approximately as $Z^4\lambda^3$ (Z^4/E^3). It is this very strong dependence of photoelectric absorption on the atomic number Z that makes lead such a good material for shielding against X-rays. For very low-atomic-numbered absorbers, the photoelectric effect is relatively unimportant.

Photonuclear Reactions (Photodisintegration)

Photodisintegration is a photonuclear reaction in which the absorber nucleus captures a high-energy photon and, in most instances, emits a neutron. This is a threshold reaction in which the quantum energy must exceed a certain minimum value that depends on the absorbing nucleus.

This is a high-energy reaction and, with few exceptions, is not an absorption mechanism for gamma rays (photons) from radionuclides. An important exception is the case of ^{9}Be, in which the threshold energy is only 1.666 MeV. The reaction $^9Be(\gamma, n)^8$Be is useful as a laboratory source of monoenergetic neutrons.

Photodisintegration is an important reaction in the case of very high energy photons from high-energy electron accelerators such as linear accelerators and electron synchrotrons.

In many shielding calculations, therefore, the photodisintegration cross sections are usually considered insignificant and are neglected. High-energy accelerators, however, produce copious amounts of high-energy (>10 MeV) photons.Photonuclear reactions, therefore, become important in shielding design. Photodisintegration is a threshold reaction because the energy added to the absorber nucleus must be at least equal to the binding energy of a nucleon.

Furthermore, a neutron is preferentially emitted rather than a proton because it has no columbic potential barrier to overcome in order to escape from the nucleus and hence has a lower threshold. The range of energy thresholds for photodisintegration by neutron emission varies from 1.67 MeV for beryllium to about 8 MeV. Quantum energies greater than the threshold appear as kinetic energy of the emitted neutrons or, if great enough, may cause the emission of charged particles from the absorber nucleus.

Combined Effects

The attenuation coefficients or cross sections give the probabilities of removal of a photon from a beam under conditions of good geometry, where it is assumed that any of the possible interactions remove the photon from the beam. The total attenuation coefficient, therefore, is the sum of the coefficients for each of the three reactions discussed above:

$$\mu_t = \mu_{pe} + \mu_{Cs} + \mu_{pp}, \qquad (3\text{-}17)$$

Where the three right-hand terms are the attenuation coeff.s for the photoelectric effect, for Compton scattering, and for pair production, respectively. In computing attenuation of radiation for purposes of shielding design, the total attenuation Coeff. as defined in Eq. (3-17) is used. Equation (3-17) gives the fraction of the energy in a beam that is removed, per unit absorber thickness.

The fraction of the beam's energy that is deposited in the absorber considers only the energy transferred to the absorber by the photo e by the Compton e, and by the e pair. Energy carried away by the scattered photon in a Compton interaction and the energy carried off by the annihilation radiation after pair production is not included. The energy absorption coeff., which is also called the true absorption coeff.

,is given by

$$\mu_e = \mu_{pe} + \mu_{Ce} + \mu_{pp}\left(\frac{hf - 1.02}{hf}\right) \quad (3\text{-}17)$$

The total attenuation and true absorption coefficients for air are shown in Fig. 3-9, and the energy absorption coefficients for water, air, compact bone, and muscle are listed in Table3-1.

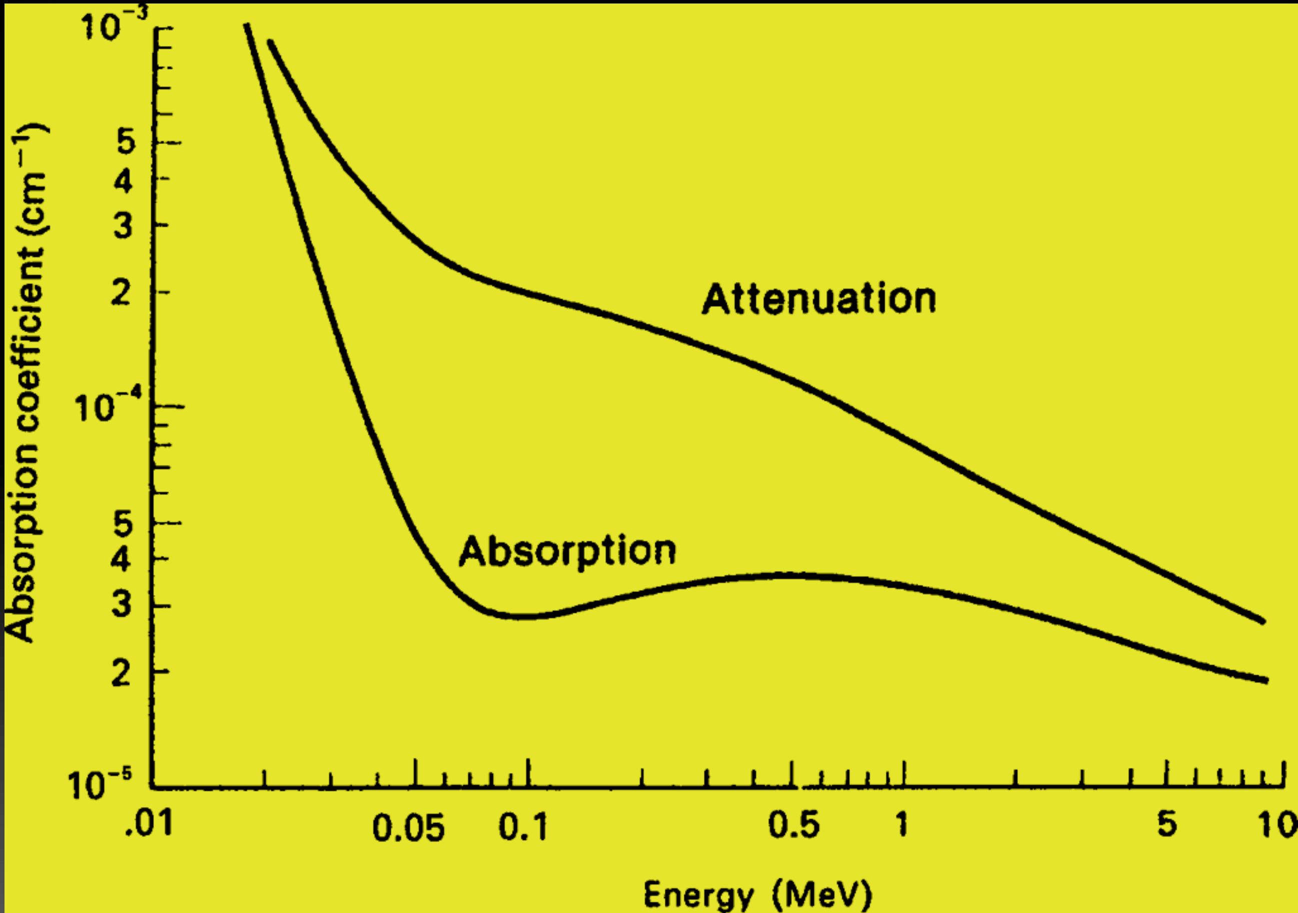


Figure 3-9. Linear attenuation coeffs and absorption coeff of air for γ rays as a function of energy.

TABLE 3-1. Values of the Mass Energy–Absorption Coeff

PHOTON ENERGY (MeV)	MASS-ENERGY-ABSORPTION COEFFICIENT $(\mu_{en}/\rho)cm^2/g$			
	Water	Air	Compact Bone	Muscle
0.010	4.89	4.66	19.0	4.96
0.015	1.32	1.29	5.89	1.36
0.020	0.523	0.516	2.51	0.544
0.030	0.147	0.147	0.743	0.154
0.040	0.0647	0.0640	0.0305	0.0677
0.050	0.0394	0.0384	0.158	0.0409
0.060	0.0304	0.0292	0.0979	0.0312
0.080	0.0253	0.0236	0.0520	0.0255
0.10	0.0252	0.0231	0.0386	0.0252
0.15	0.0278	0.0251	0.0304	0.0276
0.20	0.0300	0.0268	0.0302	0.0297
0.30	0.0320	0.0288	0.0311	0.0317
0.40	0.0329	0.0296	0.0316	0.0325
0.50	0.0330	0.0297	0.0316	0.0327
0.60	0.0329	0.0296	0.0315	0.0326
0.80	0.0321	0.0289	0.0306	0.0318
1.0	0.0311	0.0280	0.0297	0.0308
1.5	0.0283	0.0255	0.0270	0.0281
2.0	0.0260	0.0234	0.0248	0.0257
3.0	0.0227	0.0205	0.0219	0.0225
4.0	0.0205	0.0186	0.0199	0.0203
5.0	0.0190	0.0173	0.0186	0.0188
6.0	0.0180	0.0163	0.0178	0.0178
8.0	0.0165	0.0150	0.0165	0.0163
10.0	0.0155	0.0144	0.0159	0.0154